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A STUDY OF THE FUEL/AIR VAPOR CHARACTERISTICS IN THE ULLAGE OF AIRCRAFT FUEL TANKS

By

Charles M. Pedriani

June 1970

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

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A STUDY OF THE FUEL/AIR VAPOR CHARACTERISTICS IN THE ULLAGE OF AIRCRAFT FUEL TANKS

By

Charles M. Pedriani

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SUMMARY

The objective of this effort was to study fuel tank ullage characteristics under various atmospheric and dynamic conditions. A test tank was constructed and mounted on a vibration table. The tank was filled with JP-4 fuel and withdrawn at various aircraft usage rates under controlled temperature and vibration. The fuel/air ratio of the ullage was measured with an infrared analyzer, and the data were recorded.

A fuel/air ratio gradient was found in the ullage. It varied from a lean mixture (less than 1%) near the top of the tank, due to the inflow of air, to a rich mixture (as high as 12%) near the surface of the fuel, due to fuel surface oscillations. The testing indicates how this gradient is affected by changing the fuel withdrawal rate, fuel temperature, and vibrational exitation frequency.

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INTRODUCTION

The fuel/air vapor studies were initiated to reduce the vulnerability of aircraft fuel tanks to small-arms fire. The specific phenomenon studied is that of incendiary ignition of the fuel/air mixture in the ullage of the tank. In order to accurately predict this hazardous condition, two questions must be answered: (1) What are the ullage characteristics during simulated flight conditions? (2) What are the ignition characteristics of possible ignition sources, i.e., tracer and incendiary rounds?

The work reported herein attempts to answer the first question; that is, to describe the ullage characteristics under various dynamic and atmospheric conditions. As a result of knowledge gained in testing, it is hoped that, given a set of conditions, the fuel/air ratio throughout the fuel tank can be described. This basic knowledge is a valuable tool in predicting a hazardous condition and in establishing the criteria for evaluating any system to render the ullage inert.

The second question will be investigated during a subsequent effort in which tracer and incendiary rounds will be fired into a fixture containing known fuel/air ratios. The final result of this second effort should provide an accurate definition of the explosive limits of JP-4 for a varying exposure time to incendiary rounds.

BACKGROUND

Existing literature describes the ullage characteristics of containers under static conditions: the liquid is motionless; hence, there is no transfer of liquid or vapor across the walls of the tank, and the vapor appears to be concentrated uniformly throughout the vapor space. The fuel/air ratio of this ullage space depends on the vapor pressure of the liquid and, as such, varies with temperature.

Under flight conditions, the equilibrium is disturbed in two ways. First, the motion of the aircraft disturbs the surface area of the fuel; as a result, it would seem that the fuel/air ratio near the surface of the fuel would increase. Second, as fuel is withdrawn, air enters the tank through the vent, locally reducing the fuel/air ratio. Thus, it was predicted that the overall result would be a fuel/air vapor gradient within the tank. Obviously, then, the fuel/air ratio at a particular location would no longer depend only on the vapor pressure but also on the dynamic conditions of vibration and fuel withdrawal.

Under dynamic conditions, analytical prediction of the ullage characteristics becomes extremely difficult. Also, since these conditions have never been studied experimentally, it was decided to conduct such an effort.

A preliminary study was conducted to confirm the existence of a fuel/air vapor gradient under dynamic conditions.* A gradient was encountered, so a more thorough study was initiated.

Because this work is the first of its type and because it will contribute to the basic literature on the subject, it was decided to approach the work both in-house and contractually.

Dynamic Science, Irvine, California, has studied the ullage characteristics as a function of vibrational frequency, tank geometry, and atmospheric conditions. The results of those studies are reported separately. USAAVLABS has conducted tests in which the effects of fuel flow rate, vibrational frequency, and fuel temperature on ullage characteristics were studied. The results of these in-house tests are presented in this report.

*Charles M. Pedriani, THE PRELIMINARY RESULTS OF FUEL VAPOR GRADIENT TESTS, Technical Memorandum, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, March 1969 (Unpublished).

EQUIPMENT AND TEST PROCEDURES

EQUIPMENT

The test equipment, shown in Figures 1 and 2, includes an aluminum test tank (23 inches by 27 inches by 30 inches) mounted on a vibration table. The vibration fixture imparts a rocking motion to the base of the tank, using a variable-speed motor and eccentric drive. It is capable of excitations at frequencies up to 700 cpm. Six electric heaters (Figure 3) were attached to the bottom of the tank to raise the fuel temperature above ambient; an immersion cooling unit (Figures 4 and 5) was used to lower the fuel temperature below ambient. Six thermocouples and a pyrometer permitted close observation of the temperature. A large plastic pump with viton impeller connected to a variable-speed (1/2-horsepower) motor was used to pump the fuel at rates from 1/2 gpm to 8 gpm as required.

An MSA Lira infrared triple-span analyzer was used to monitor the vapor content of the ullage. A single, manually adjusted probe mounted in the center of the tank was used to withdraw the sample.

Figure 1. Test Tank Being Filled During Check-Out Tests.

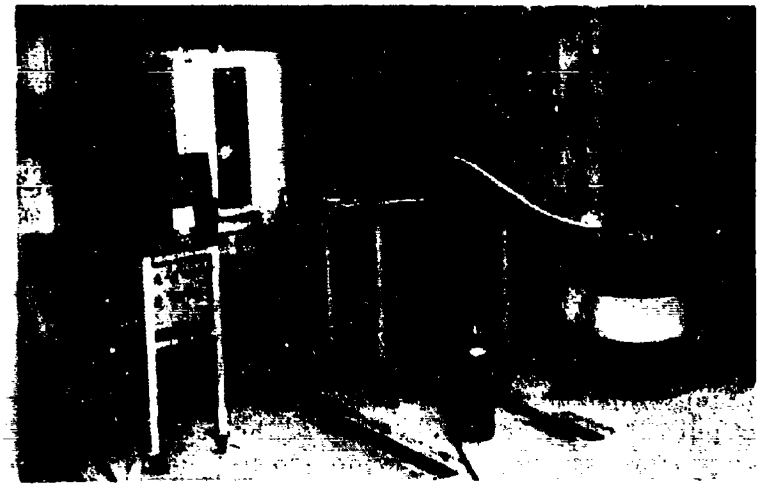


Figure 2. Test Equipment in Readiness on Site.

Figure 3. Electric Heaters Installed in Base of Test Tank.

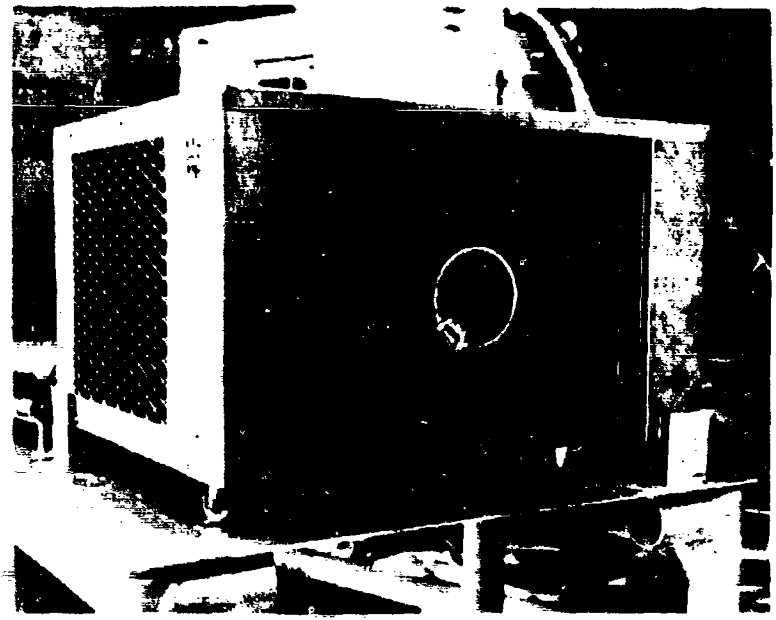


Figure 4. Cooling Unit Used for Testing at Fuel Temperatures Lower Than Ambient.

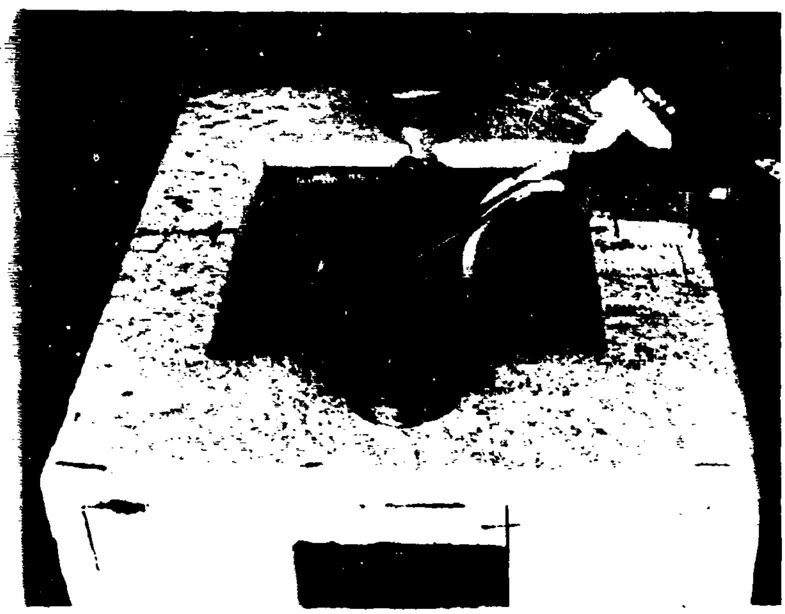


Figure 5. Immersion Coil of the Cooling Unit in Operation.

TEST PROCEDURES

The test tank was filled by an Army aircraft service tanker. The JP-4 conformed to MIL-T-5624. The temperature conditioning was started immediately if the test temperature was other than ambient.

Since no automatic control devices were available, the heater and cooler were manually controlled to achieve the desired temperature. Prior to each test run, the analyzer was calibrated using the zero (nitrogen) and calibration (hexane in nitrogen) gases. After the fuel was conditioned, the vibration table was started and the exitation frequency was adjusted. Then, as the fuel was withdrawn at the desired rate, data were recorded. Also, small samples were withdrawn and distillation analyses were made.

In addition to a small 15-lb fire extinguisher (Figure 2), eight 50-lb CO_2 bottles were provided at the site as a safety measure.

RESULTS

GENERAL

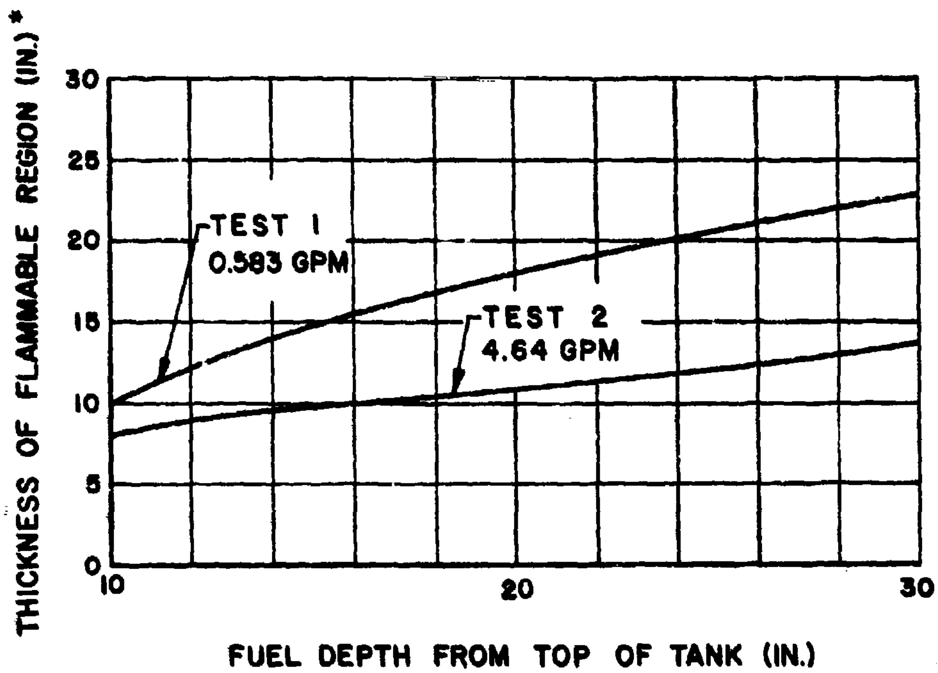
In all tests in which flight conditions were simulated, a fuel/air vapor gradient was encountered. In every case, this gradient extended into the flammable range; therefore, at least a portion of the ullage was in a hazardous condition. The experimental confirmation of this hazardous condition is an important result of this study; but equally important is the knowledge gained of how the fuel/air ratio within the ullage is affected by environmental conditions.

It was found that a low fuel-withdrawal rate provides more time for the vapors to diffuse from the fuel surface, hence increasing the vapor content of the ullage. In addition, both fuel vibration and an increase in fuel temperature result in a higher vapor content. However, keeping in mind the flammable limits of JP-4 (about 1.3 to 8.1% by volume), a simple increase or decrease must be large enough to drive the entire ullage out of this range before a hazardous condition is eliminated.

Detailed results of the fuel/air vapor tests under dynamic conditions are presented in Appendix I. Results of the tests under static conditions are presented in Appendix II.

FUEL OUTFLOW RATE

In tests 1 and 2, the outflow rates were 0.583 gpm and 4.64 gpm respectively. Plotting the flammable volume (Figure 6) shows that the volume was greater using a lower withdrawal rate. More can be learned, however, by looking at the curves in Appendix I. With a slow withdrawal, the elapsed time from data point to data point was increased with no increase in the amount of air entering the vent. Therefore, the vapors were given more time to diffuse throughout the tank. Hence, the lower withdrawal rate tends to increase the fuel/air ratio within the tank, particularly near the top of the tank. Under these particular conditions of temperature and vibration frequency, the overall increase in fuel/air ratio resulted in an increase in flammable volume.



* A MEASURE OF THE FLAMMABLE VOLUME, SINCE THICKNESS X CROSS SECTION AREA = VOLUME.

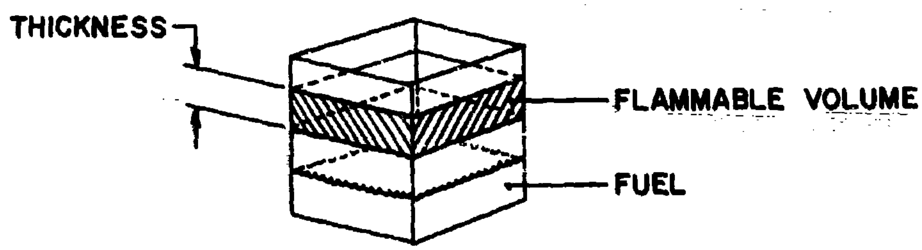


Figure 6. Flammable Volume Versus Fuel Depth.

VIBRATIONAL FREQUENCY

The effects of vibrational inputs on the ullage were studied in tests 2, 3, and 6, in which frequencies of 324, 547, and 0 cpm, respectively, were used. These results are summarized in Figure 7 and shown in detail in Appendix I.

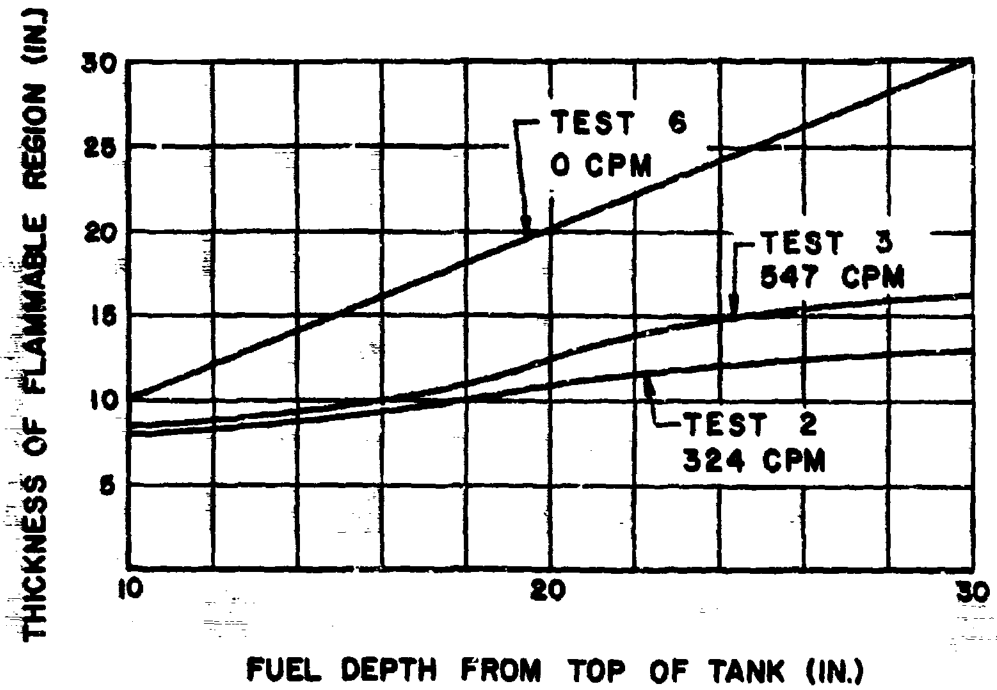
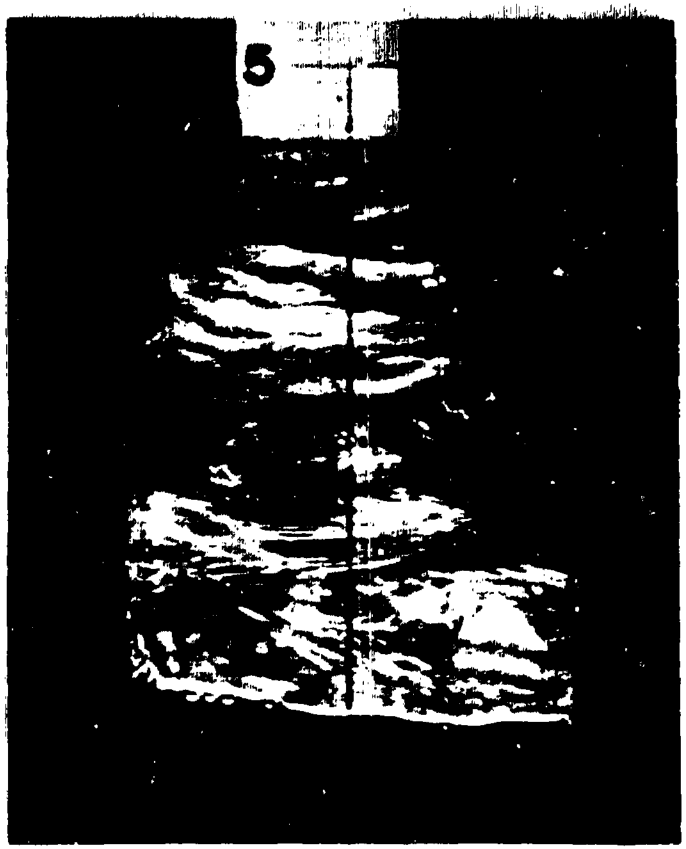


Figure 7. Effect of Vibration on Flammable Volume.

The data taken in tests 2 and 3 show that the increased exitation frequency caused a small increase in the amount of vapor in the ullage and a corresponding small increase in the flammable volume. This increase was apparently caused by the larger fuel surface area associated with the higher frequency visible in Figure 8. As expected, the increase in fuel/air ratio was manifested near the surface of the fuel.



(a) Vibrational Frequency, 325 cpm.

(b) Vibrational Frequency, 623 cpm.

Figure 8. Response of Fuel to Vibrational Inputs (Fuel Level, 10 Inches From Top of Tank).

The shape of the curves in test 6, with no vibration, indicates an entirely different ullage condition. A certain amount of vapor was present at the start of the test, and as the fuel was drained, little or no additional vapor was added. Therefore, as the ullage volume increased, the fuel/air ratio continually decreased because of the influx of air. However, in spite of the lower overall vapor content, the entire ullage was within the limits of flammability. This hazardous condition could possibly be a result of a lack of vapor gradation in the ullage. The difference in results between tests with and without vibration is clear. In fact, the difference between low frequency and high frequency is not as significant as that between no-vibration and vibration. The ullage characteristics depend more on whether or not there is vibration than on the frequency of that vibration.

FUEL TEMPERATURE

The fuel temperature was varied from 12° to 110°F in tests 8, 9, 10, 11, and 14. A side-by-side comparison of these results shows that they were qualitatively similar. That is, a vapor gradient was observed in all tests, and the form of the curves follows the same general outline. Quantitatively, however, they are different. The overall vapor content increased, with the temperature driving the resultant curves more to the right. This behavior was expected since at higher temperatures the vapor pressure will rise, resulting in more fuel molecules being released to the ullage. Although the vapor content increased with temperature, the flammable volume did not. Figure 9 shows that the flammable volume reached a maximum at 50°F in test 10. At low temperatures, a small portion of the ullage near the fuel was in a flammable condition, contrary to the static data, which indicate a nonflammable condition. This flammable condition was probably a result of the surface oscillation. The remainder of the ullage was in a lean condition.

As the temperature increased in test 9, the curves shifted more into the flammable range, increasing the flammable volume. The upper portion of the ullage was still in a lean condition.

In test 10, the curves shifted more to the top. In addition, less of the ullage was in the lean mixture; thus, the flammable volume reached its maximum in this test.

In test 11, the curves shifted far enough to the top to render the ullage near the fuel in an over-rich condition, thus reducing the flammable volume.

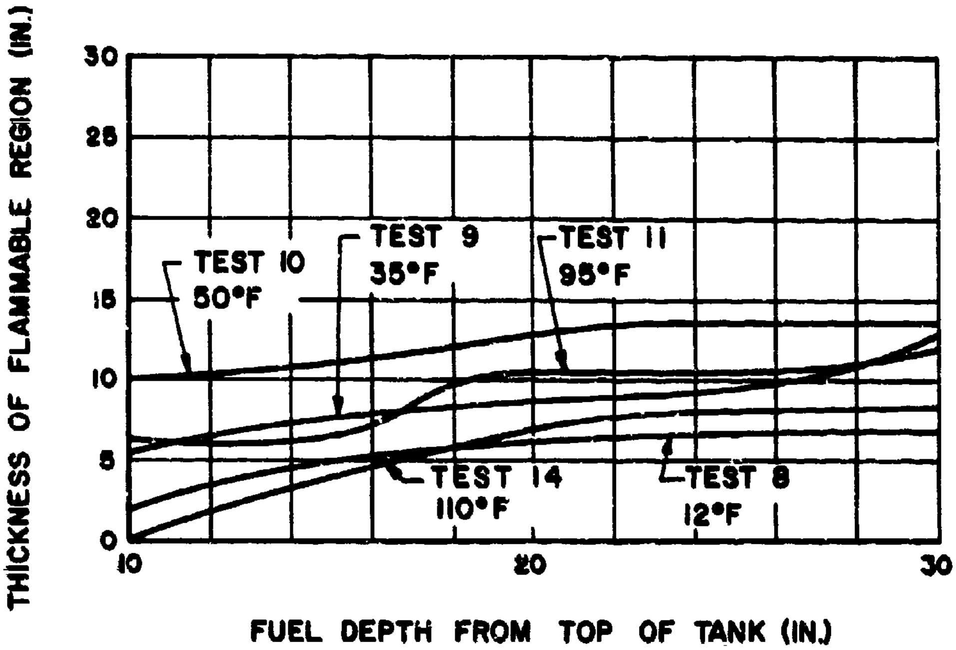


Figure 9. Effect of Temperature on Flammable Volume.

STATIC TESTS

Several tests were run with no dynamic conditions. The test tank was simply filled to a certain level and left undisturbed. The ullage was then monitored at prescribed depths and intervals as shown in Appendix II. The results show that the ullage becomes a uniform concentration in less than 5 minutes and remains stable for long periods of time.

The vapor gradient in all these tests was extremely small, 1 to 2%, as compared with that in the dynamic tests.

As shown in Figure 29, the ullage was sampled once about 0830 and then left undisturbed until about 1330, when it was monitored again. It can be seen that the vapors tended to settle over this long period of time, but the gradient was still comparatively small.

ADDITIONAL TESTS

Several tests were run more than once in order to establish the repeatability of the results. Tests 2 and 7, 4 and 5, 8 and 10, and 11 and 15 were run under approximately the same conditions; and as can be seen by inspection, the results are repeatable.

Prior to test 4, three bags of 3/4-inch-diameter plastic floating spheres (1000 per bag) were added to the tank, resulting in about a 2-inch layer on top of the fuel (compare tests 2 and 4). Tests 4 and 5 were run at about the same test conditions and produced similar results. The only difference between these tests was the method of filling the test tank. In test 4, the tank was filled directly from the tanker to the top of the tank, permitting the fuel to free-fall onto the spheres. In test 5, the fuel was pumped into the tank beneath the spheres. It was anticipated that the wetting of the spheres would have an effect on the results, but it did not.

In test 17, only one bag of spheres was added. This test was motivated by the results of the gradient tests,* wherein the MINIVAPS increased the fuel/air ratios by increasing the effective surface area. It was hoped that the ratio would be increased enough to render the tank less hazardous. It was found, however, that even though the spheres damped the fluid motion as in tests 4 and 5, the fuel/air ratio was similar to that in the tests without spheres (compare tests 7 and 17).

Two tests (12 and 13) were run with JP-8 fuel. The results of these tests are not shown because little or no vapor was detected during the tests. For example, the highest reading obtained was only 0.07%, with a fuel temperature of 95°F.

Finally, reticulated polyurethane foam was installed in the tank, and an attempt was made to sample the ullage. The attempt was unsuccessful. The readings were erratic, probably because of an uneven sample being drawn into the analyzer.

*Ibid.

CONCLUSIONS

It is concluded that:

1. Under dynamic conditions, fuel vapor within the flammable range exists in Army aircraft fuel tanks using JP-4 fuel over a minimum temperature range of 12° to 110°F.

2. Temperature is the primary variable affecting the overall vapor content and the flammable volume. However, small changes in the vapor content may be effected by a change in fuel withdrawal rates or vibrational frequency.

3. The use of JP-8 fuel would significantly reduce hazardous vapor in the ullage of fuel tanks.

RECOMMENDATIONS

It is recommended that:

1. Design concepts be investigated to eliminate the hazardous conditions found in this test. The operating environment of Army aircraft during low-altitude low-speed flight should not be neglected in an attempt to find a simple solution.

2. Additional tests be conducted to evaluate the effect of altitude and flight profiles on the ullage characteristics.

3. Tests to determine the flammable limits of JP-4 as a function of incendiary and tracer ignition be expedited. It is possible that the limits of flammability defined in this manner may be entirely different from the 1.3 to 8.1% used in this test.

APPENDIX I

RESULTS OF FUEL/AIR VAPOR TESTS UNDER DYNAMIC CONDITIONS

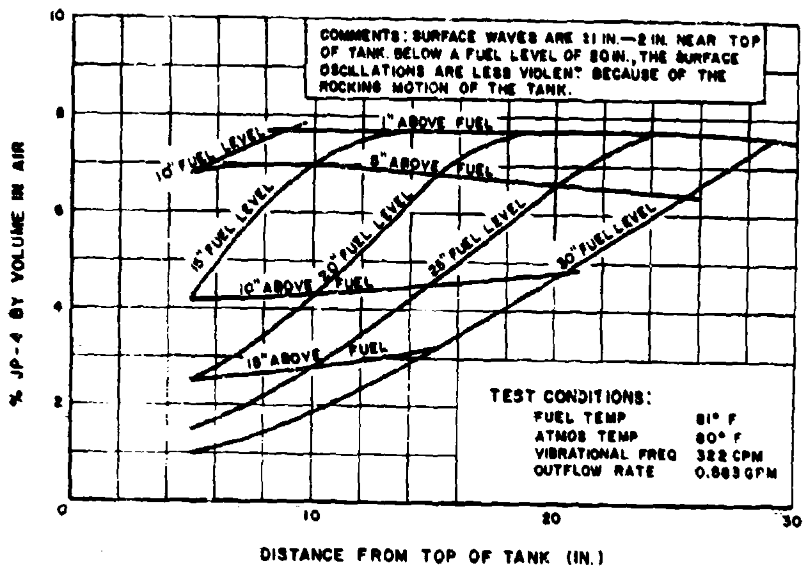


Figure 10. Results of Test 1.

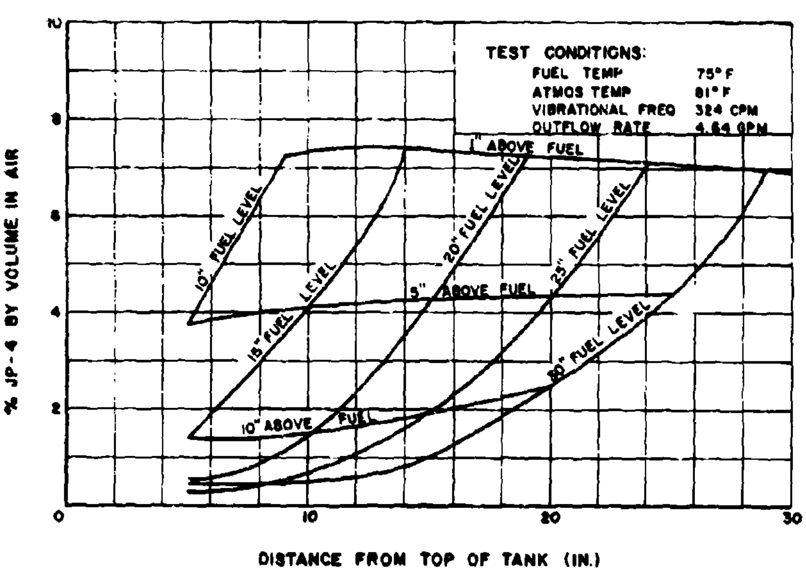


Figure 11. Results of Test 2.

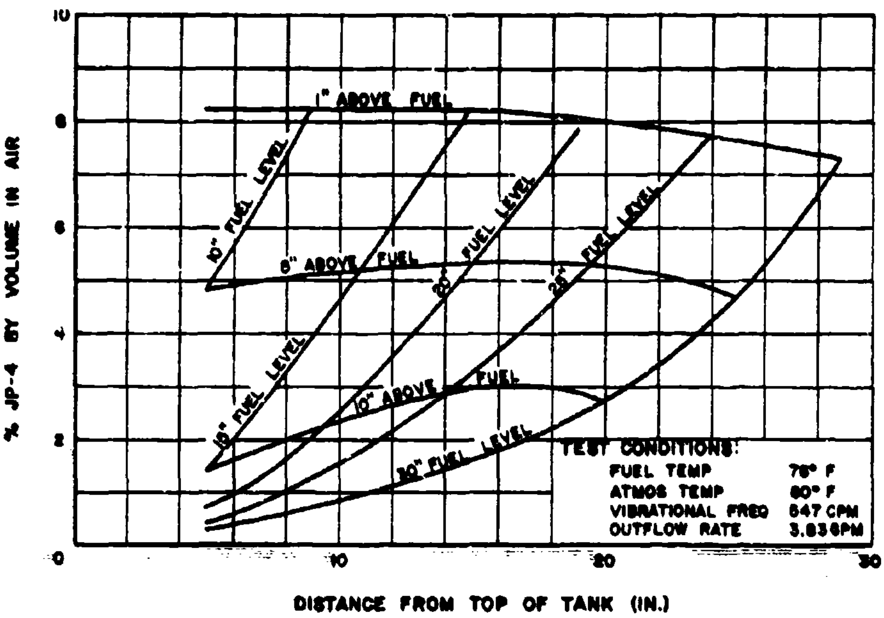


Figure 12. Results of Test 3.

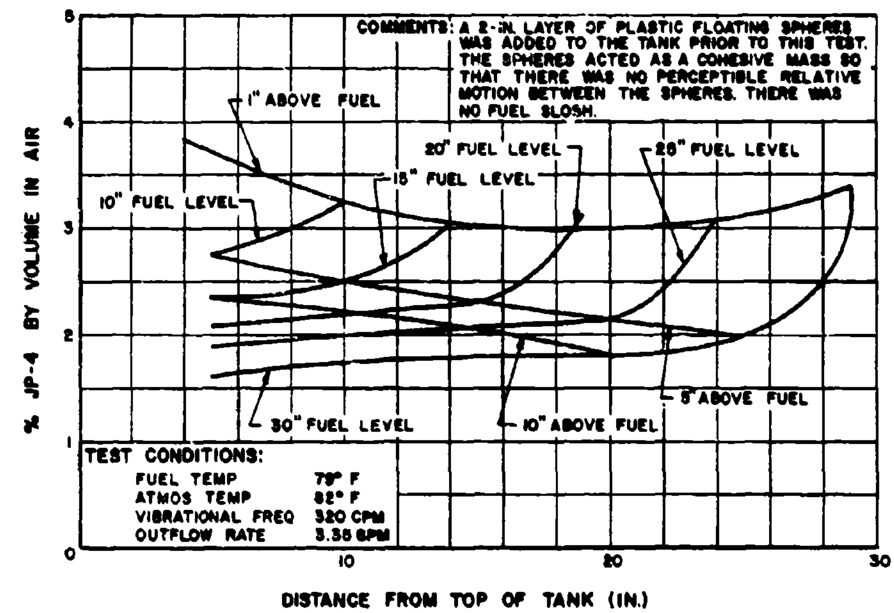


Figure 13. Results of Test 4.

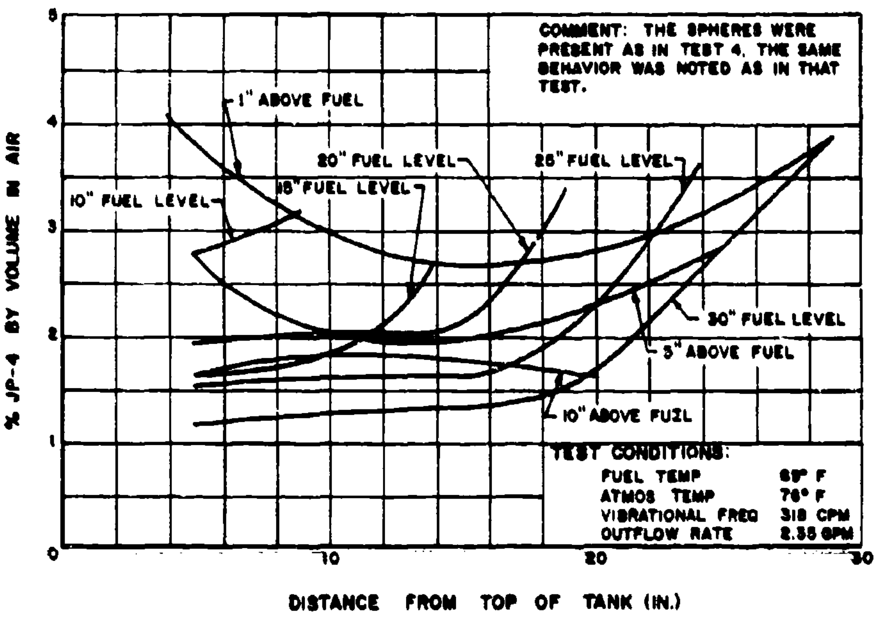


Figure 14. Results of Test 5.

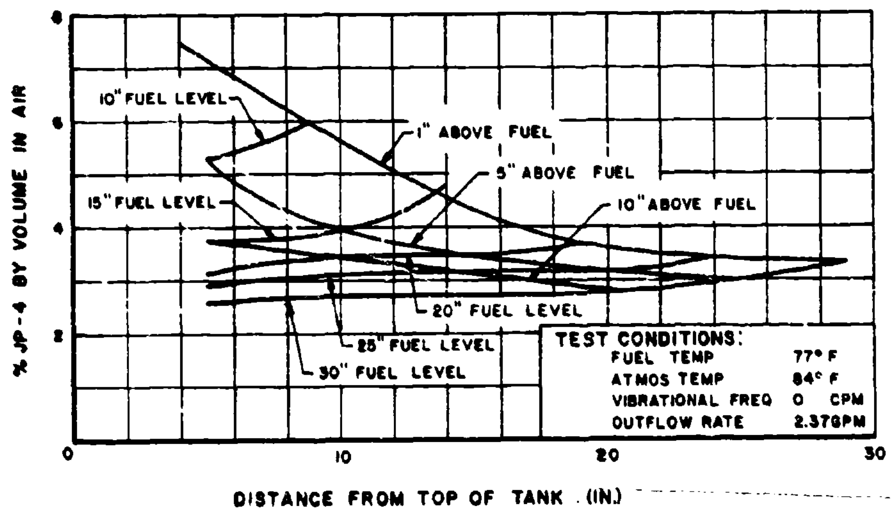


Figure 15. Results of Test 6.

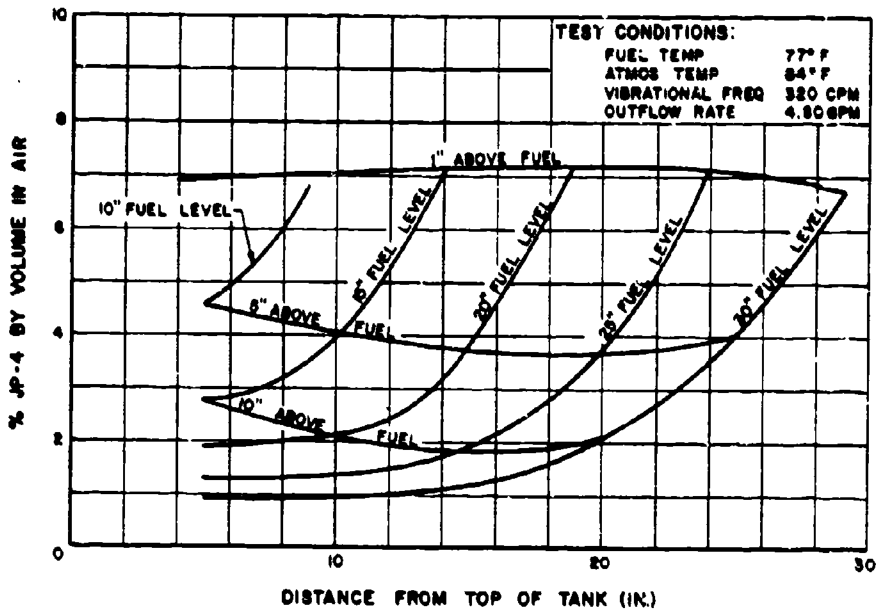


Figure 16. Results of Test 7.

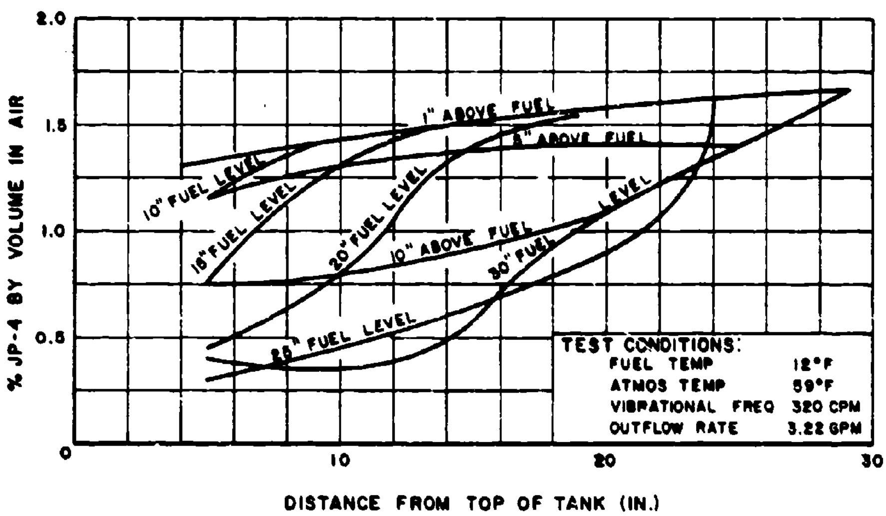


Figure 17. Results of Test 8.

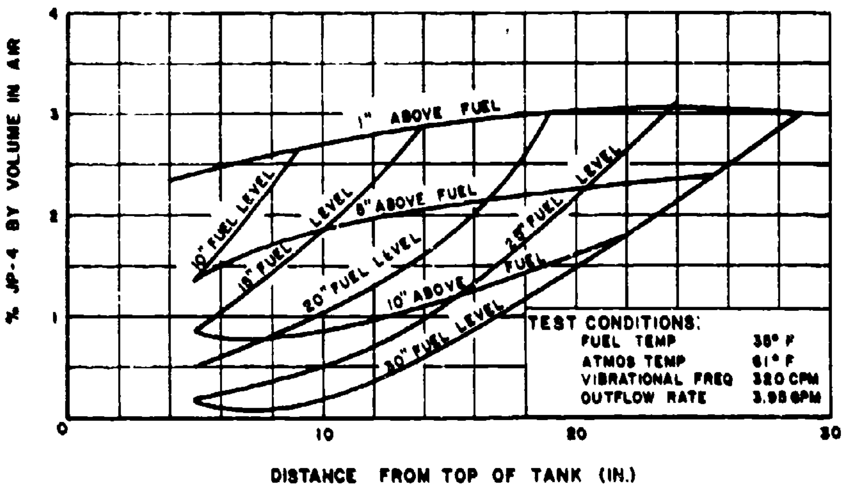


Figure 18. Results of Test 9.

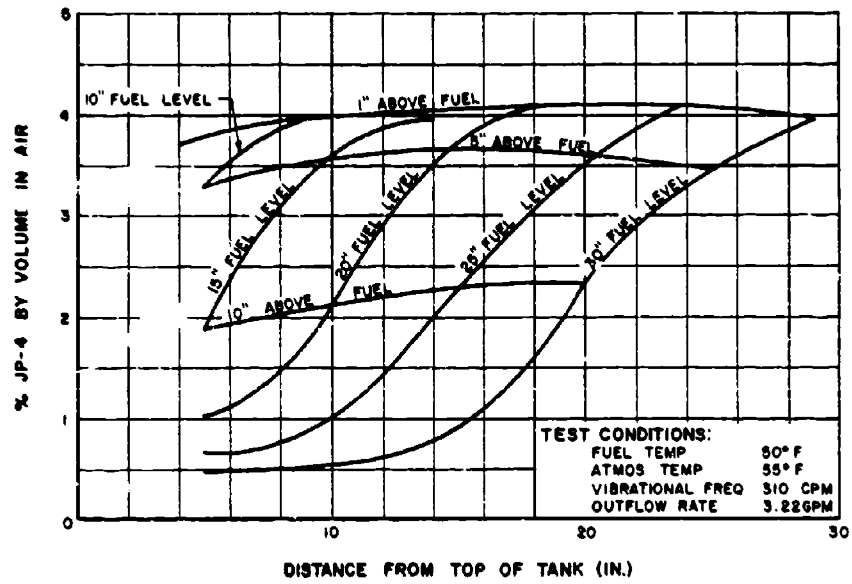


Figure 19. Results of Test 10.

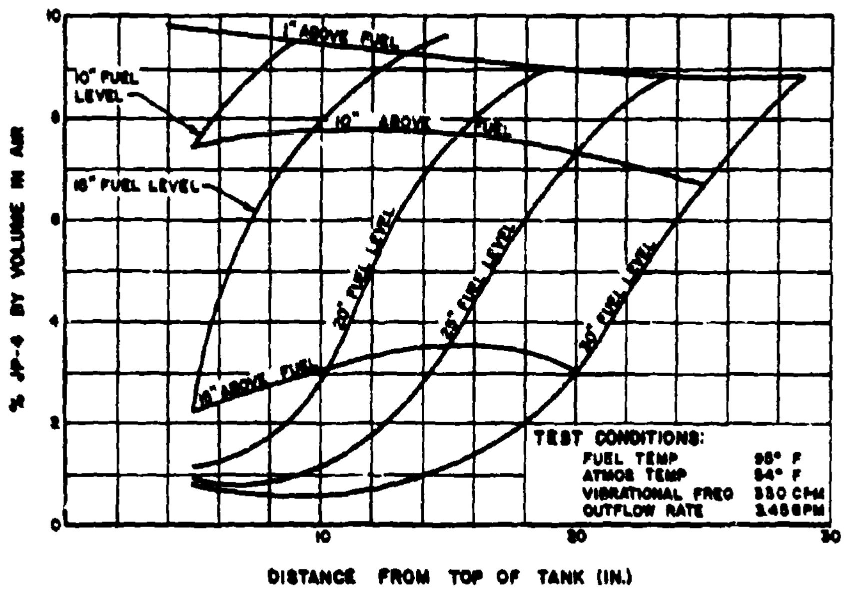


Figure 20. Results of Test 11.

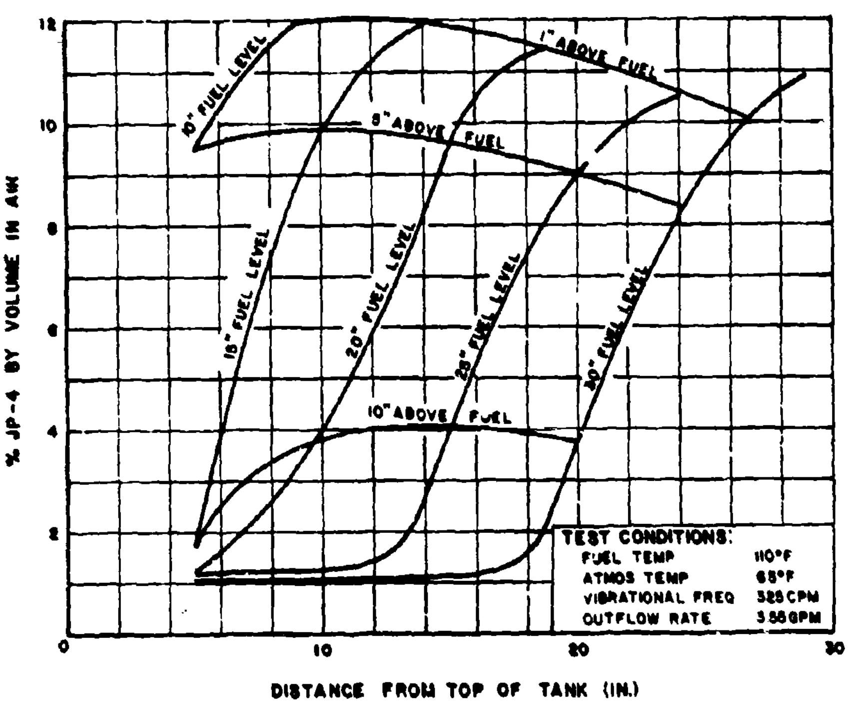


Figure 21. Results of Test 14.

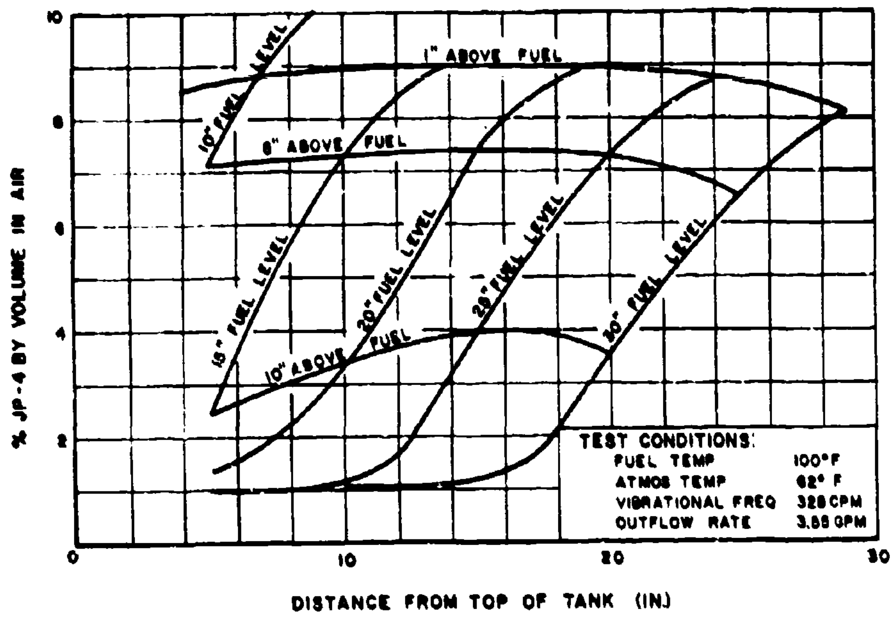


Figure 22. Results of Test 15.

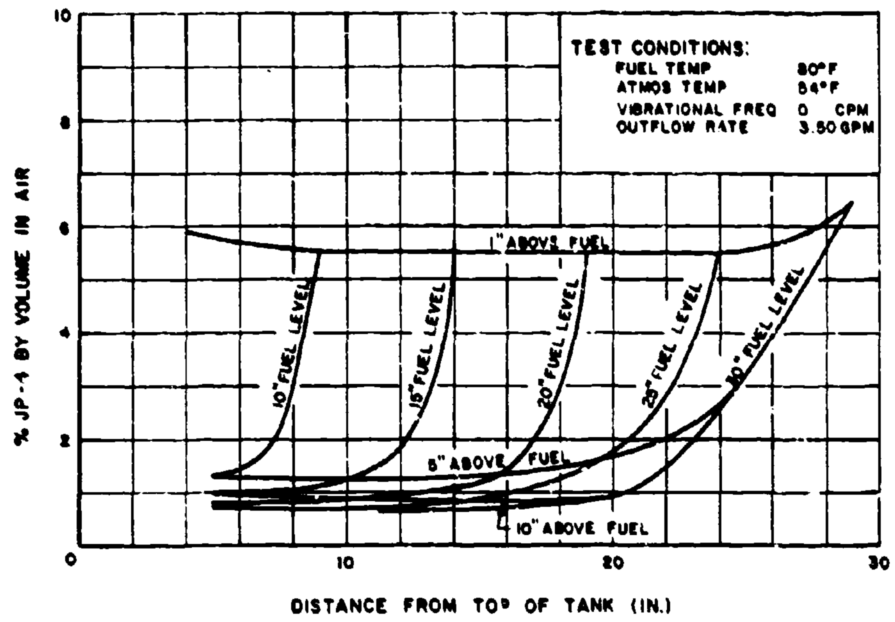


Figure 23. Results of Test 16.

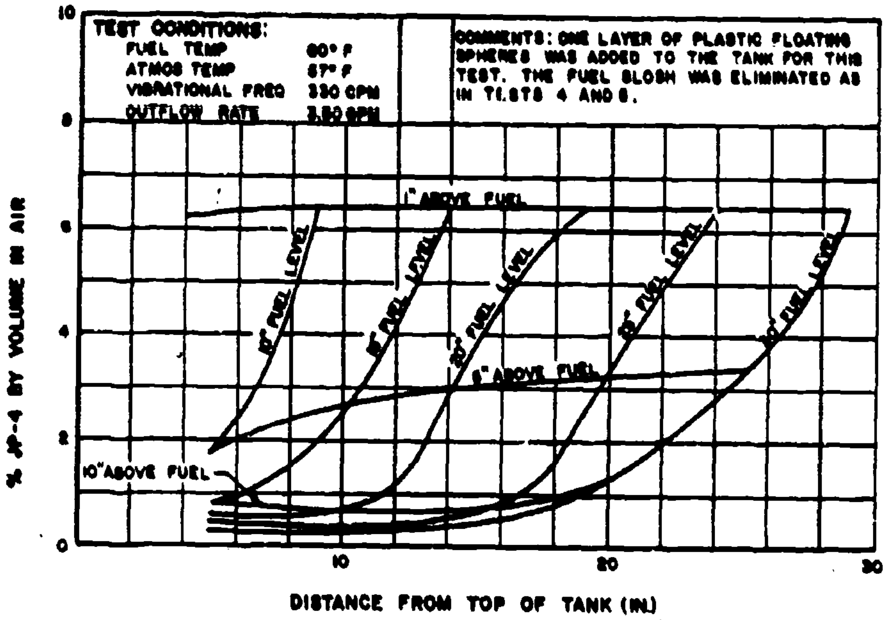


Figure 24. Results of Test 17.

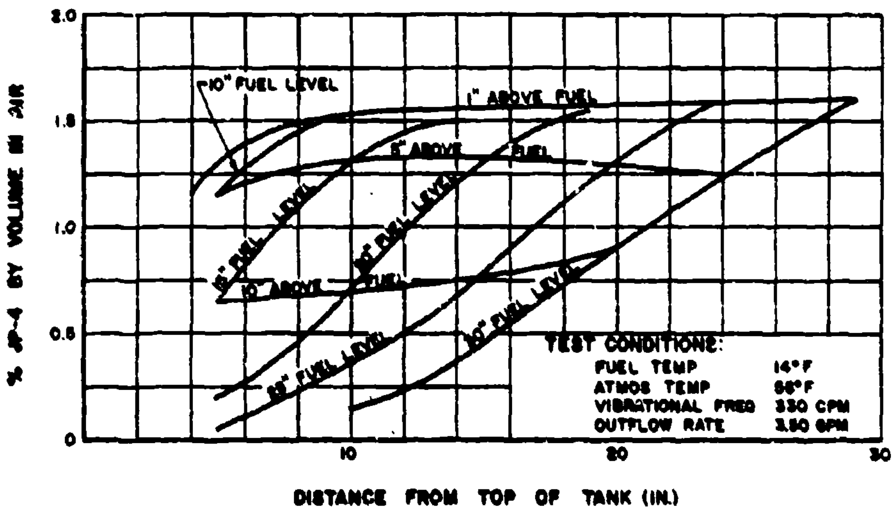


Figure 25. Results of Test 18.

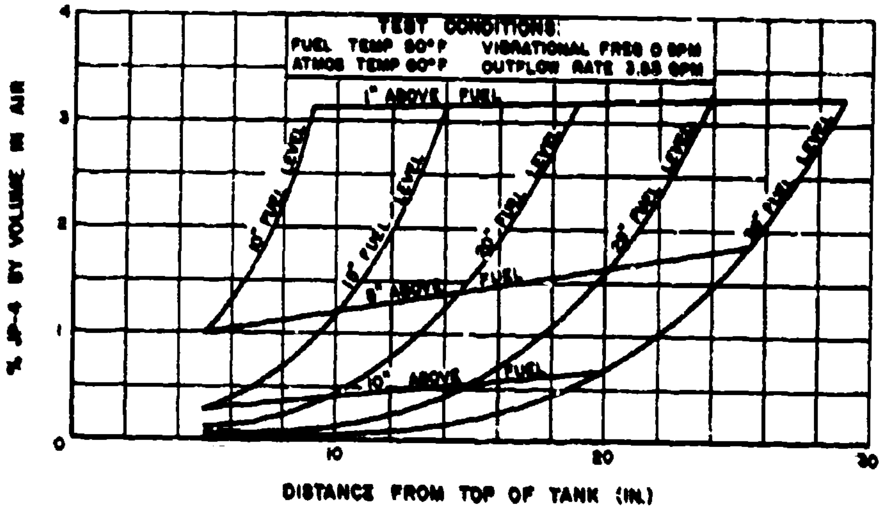


Figure 26. Results of Test 19.

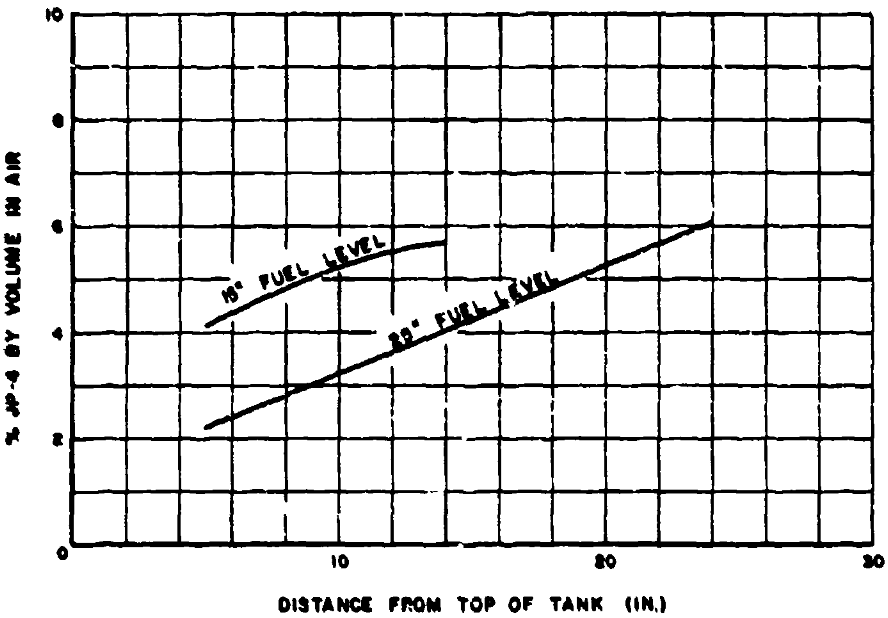


Figure 27. Results of Static Test - 87°F Temperature (15 Minutes After Fill).

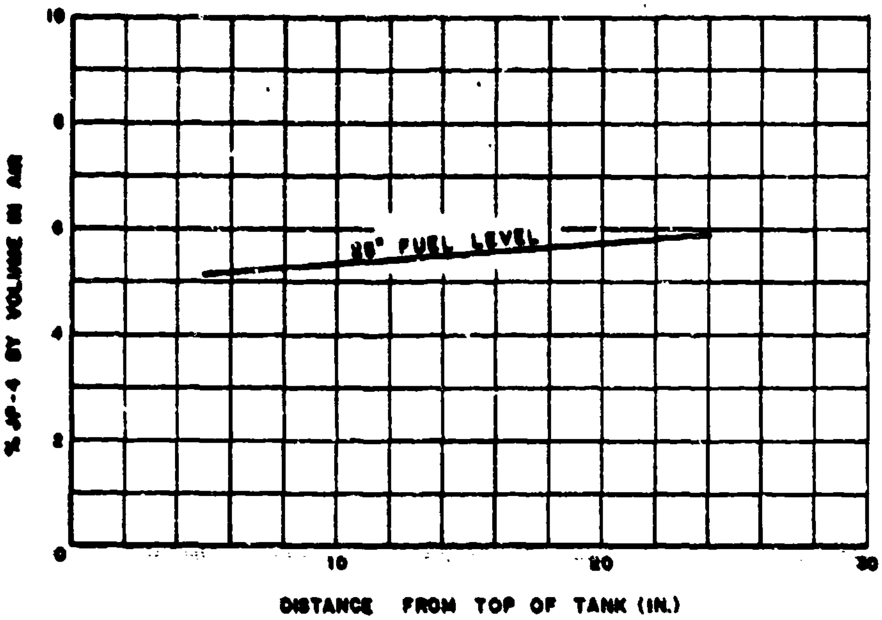


Figure 28. Results of Static Test - 72°F Temperature (15 Minutes After Fill).

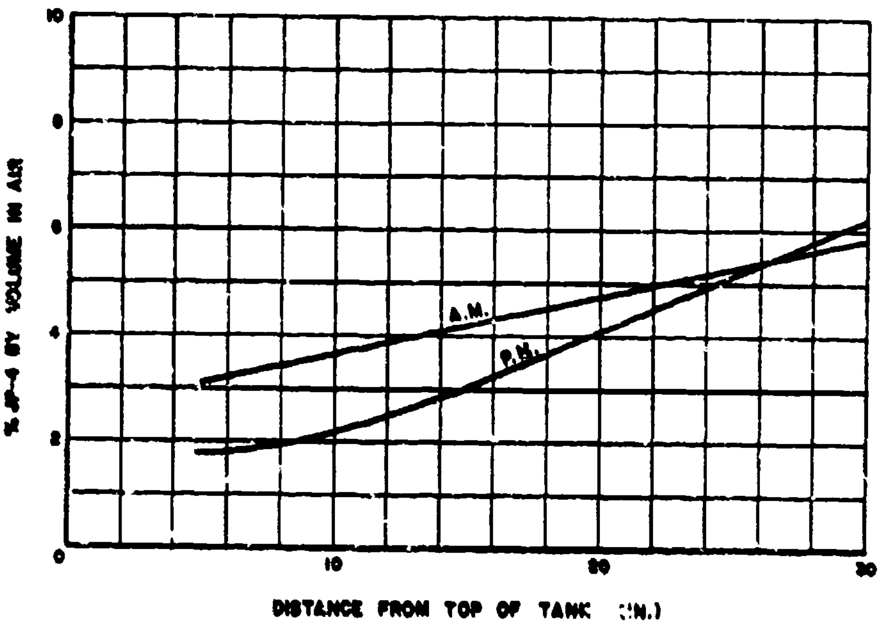


Figure 29. Results of Static Test (Tank With 1 Inch of Fuel Stabilized).

APPENDIX II

RESULTS OF FUEL/AIR VAPOR TESTS UNDER STATIC CONDITIONS

TABLE I. % JP-4 BY VOLUME, STATIC TEST - FUEL LEVEL, 25 IN.; ATMOSPHERIC TEMPERATURE, 84°F

Probe Height (in.)	Time After Fill (min)			
	5	15	30	45
5	4.00	3.80	3.68	3.50
10	4.35	4.31	4.17	4.00
15	4.63	4.55	4.50	4.35
20	4.90	4.83	4.75	4.70
24	5.40	5.30	5.30	5.30

TABLE II. % JP-4 BY VOLUME, STATIC TEST - FUEL LEVEL, 15 IN.; ATMOSPHERIC TEMPERATURE, 84°F

Probe Height (in.)	Time After Fill (min)			
	5	15	30	45
5	4.35	4.31	4.31	4.17
10	5.30	5.20	5.20	5.10
14	5.75	5.70	5.70	5.70

TABLE III. % JP-4 BY VOLUME, STATIC TEST - FUEL LEVEL, 25 IN.; ATMOSPHERIC TEMPERATURE, 87°F

Probe Height (in.)	Time After Fill (min)			
	5	15	30	45
5	2.30	2.30	2.30	2.72
10	3.13	3.18	3.18	3.40
15	4.06	4.06	4.06	4.31
20	5.20	5.20	5.20	5.53
24	6.10	6.10	6.10	6.30

TABLE IV. % JP-4 BY VOLUME, STATIC TEST - FUEL LEVEL, 15 IN.; ATMOSPHERIC TEMPERATURE, 87°F

Probe Height (in.)	Time After Fill (min)			
	5	15	30	45
5	4.17	4.25	4.45	4.83
10	5.53	5.40	5.63	5.75
14	*	6.20	6.30	6.55

*Probe accidentally submerged in fuel.

TABLE V. % JP-4 BY VOLUME, STATIC TEST - FUEL LEVEL, 25 IN.; ATMOSPHERIC TEMPERATURE, 72°F

Probe Height (in.)	Time After Fill (min)			
	5	15	30	45
5	5.30	5.20	5.20	4.90
10	5.50	5.30	5.40	5.30
15	5.60	5.50	5.60	5.60
20	5.70	5.60	6.00	6.00
24	6.10	5.90	6.10	6.20

TABLE VI. % JP-4 BY VOLUME, STATIC TEST - FUEL LEVEL, 1 IN.

Probe Height (in.)	Morning	Afternoon
5	3.18	1.78
10	3.68	2.20
15	4.17	3.00
20	4.63	4.00
25	5.30	5.30
30	5.90	6.20

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Security Classification

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13. ABSTRACT

The objective of [illegible] effort was to study fuel tank ullage characteristics under various atmospheric and dynamic conditions. A test tank was constructed and mounted on a vibration table. The tank was filled with JP-4 fuel and withdrawn at various aircraft usage rates under controlled temperature and vibration. The fuel/air ratio of the ullage was measured with an infrared analyzer, and the data were recorded.

A fuel/air ratio gradient was found in the ullage. It varied from a lean mixture (less than 1%) near the top of the tank, due to the inflow of air, to a rich mixture (as high as 12%) near the surface of the fuel, due to fuel surface oscillations. The testing indicates how this gradient is affected by changing the fuel withdrawal rate, fuel temperature, and vibrational excitation frequency.

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